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WALL FLAME CORRELATIONS AND UPWARD FLAME SPREAD IN A VERTICAL CHANNEL AND ITS RELEVANCE TO FIRE SAFETY

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ABSTRACT
Experimental results on wall flame behavior and upward flame spread within vertical channels of different width/depth ratios without external radiation are shown. It has been found that flame height and wall flame heat transfer become significantly higher in a channel with the width/depth ratio not larger than unity. Significant acceleration of flame spread has also been observed in a channel covered with Douglas Fir Particleboards for the similar range of the width/depth ratio. This shift of wall flame and flame spread to risky side in a channel is believed to be due to the restriction of air entrainment, radiation feedback among surfaces within the channel and increase of effective pyrolysis area.
Key Words: *flame height, heat flux, upward flame spread, vertical channel.*

INTRODUCTION

Upward turbulent flame spread is one of the fire problems in which the progress of scientific understanding during the last decade has been the most evident. Recent comparisons between theories and experiments suggest a considerable capability that thermal models can predict upward flame spread using bench-scale test data with reasonable accuracy for engineering purposes[1,2]. However, all these achievements are still limited to the application to a flat vertical surface, although lining materials are very often grooved or uneven in end-use conditions for acoustic performance or for other architectural-design purposes. Theoretical modeling of upward flame spread for uneven vertical surface may not be easy; however, practice through fire experiences and large full-scale fire tests suggests possible significant augmentation of fire hazard in grooved or channeled vertical, or, inclined surfaces[3,4,5]. Also recent experimental works on inclined surfaces suggest notable influence of sidewalls on the flame and flame spread[6,7]. Theories of upward flame spread for flat walls suggest the primary importance of the preheating of unburnt surface beyond the pyrolysis front by wall flame and external radiation sources[2,8,9,10,11,12], and any effect enhancing this preheating is believed to accelerate flame spread. Possible increase of fire hazard on a grooved or channeled surface may result from:

(1) greater flame length in a vertical groove or channel than over an even wall due to the restriction of entrainment of air to the flame

(2) decreased loss of radiation from the wall surface to ambiance due to the radiation feedback between the surfaces within the groove or the channel

(3) increase of effective pyrolyzing surface area

Although it is not the central problem discussed in this particular study, it is important to note that the mechanisms (1) and (2) can be a cause for raising fire hazard even along an incombustible dented surface as typically seen in the flame projection from a window on a facade with sidewalls[5]. Also acceleration of upward flame spread and heat release rate on parallel vertical PMMA slabs due to the similar mechanism has been demonstrated experimentally[13]. The restriction of air entrainment may further increase the wall heat transfer by the induction of the flame flow onto the wall surface(Coanda effect). The mechanism(3) may increase flame height, since the height of a wall flame is controlled essentially by the heat release rate per unit width of the projected vertical plane of the pyrolysis zone. Previous analysis already suggests the significant sensitivity of flame spreading velocity to the heat release rate per unit width[12]. This study intends to correlate such measures as flame height, wall flame heat transfer and flame spreading velocity against W/D ratio, the aspect ratio of the cross-sectional groove or channel space using experimental facilities available in the *"laboratory-attic"* as a first quantitative approach to evaluating the configuration effects in wall fires along a dented wall.

EXPERIMENTAL ARRANGEMENTS

Two series of tests, steady flame measurements and flame spread tests, have been conducted using almost identical experimental arrangements. A 0.2m x 1.0m rectangular propane burner consisting of five 0.2m square porous burner-elements has been used as the heat/ignition source for both series of the experiments. The burner was originally built for a study of fuel-shape effects on turbulent diffusion flames[14], and was designed such that fuel supply rate of each square burner-element can be controlled independently. The burner was placed against a 12mm thick, 2.4m tall vertical mineral fibre reinforced cement board surface, and sidewalls of the same material were attached to the wall above the sides of the burner to make a favorable aspect ratio(Figure 1). Fuel gas was supplied only to the burner elements surrounded by the backwall and the sidewalls. This arrangement makes it possible to produce varieties of W/D ratios within the range of W/D=1/5～5. No external radiation source has been used. In the previous upward flame experiments with flat Douglas Fir Particleboards, it has been already established that upward flame spread on this material never develop much if only the surface is flat and external radiation is not applied on the specimen[1].

Steady Flame Tests

The steady flame tests were conducted to see the influence of the channel geometry on the flame height and wall flame heat transfer quantitatively. This measurement is believed to provide basic informations on the first two possible mechanisms which may increase fire hazard in a vertical channel. Flame height and incident heat flux measurement were made using Video camera and 12.5mm diameter Schmidt-Boelter heat flux gages after the surface heat flux had reached steady state at each steady flame test. Reported values of flame height are average of the maximum flametips height for three minutes observed by eyes with the interval of one second on the Videotape records. Flame height was correlated against the modified dimensionless heat release rate, which is defined as[14]

$$Q^*_{mod}=Q/\rho_o C_p T_o g^{1/2} W D^{3/2} \qquad (1)$$

where Q is the heat release rate estimated assuming the complete combustion. Heat flux and flame height were measured along the vertical centerline of the backwall and along the corner between the backwall and one sidewall, since during preliminary tests it had been already observed that flame tends to become taller at the corner than at the center of the backwall. This local flame development is attributed to the mechanism that characterizes room corner fires, and is believed to be important from the firesafety point of view. Each heat flux gage at the corner was installed on the sidewall, with its center 15mm apart from the real corner. In order to compare the flame in a vertical channel with that over an unconfined flat wall, measurement of wall heat flux and flame height was also made using the same instrumentation without the sidewalls.

Flame Spread Tests

The flame spread tests were conducted using 12.5mm thick Douglas Fir Particleboard(" *Versaboard*") covering the incombustible backwall and sidewalls. The propane burner used as the heat source was kept on until the end of each test. Measurements were made on surface heat flux, flame height and heat release rate. Heat release measurement was made by the oxygen consumption method using O_2, CO and CO_2 monitoring. Heat flux and flame height measurements were made using the identical sensors with the steady flame tests; however, measurements were started at the ignition to the propane burner elements. Flame spread tests with Particleboard only on the backwall and with water-cooled copper sidewalls were conducted to compare the flame spread in vertical combustible channels with that on an unconfined combustible surface. The Particleboard specimens were conditioned for at leat one week before test. Water content of the specimens just before test varied from 8.1% to 9.0 %.

STEADY-FLAME CORRELATIONS IN A VERTICAL CHANNEL

Flame Height

Flame height measured on a flat wall, at the backwall in a channel, and at its corner are summarized against Q_{mod}^* for different aspect ratios of the burner in Figure 2. The experimental parameters, γ and n, for the flame height represented as

$$L_f/D=\gamma \cdot Q_{mod}^{*n} \qquad (2)$$

are summarized in Table 1. It is noteworthy, in Figure 2, that influence of the aspect ratio of the heat source becomes much less significant in a channel than on a flat wall, although it is natural since sidewalls are generally believed to make the flame closer to a two-dimensional flow, especially in the large Q_{mod}^* domain. Figures 2(b) and (c) suggest merging of the L_f/D-Q_{mod}^* relation into the line-fire correlation at Q_{mod}^* greater than the present test conditions for a channel fire. Flame flow closer to a two-dimensional one in a channel than on a flat wall may be endorsed by the n value close to 2/3, the theoretical value for a line fire, in a channel irrespective of the W/D ratio as seen in Table 1, whilst n value for relatively small W/D ratio without sidewalls for a flat wall is between 2/3 and 2/5, the theoretical value for a point source fire. As a result of this fluiddynamic effect, flame height in a narrow channel becomes significantly taller than on an unconfined wall; flame height in a channel for W/D=0.5 is found to be approximately 1.8 times the unconfined wall flame height for Q_{mod}^* less than unity. Flame height in a channel is always larger at the corner than at the center of the backwall. The difference was the most pronounced for the W/D ratio between 2.0 and 3.0. The difference is found to be ignorable for $W/D \leqq 1.0$, and is less significant for W/D greater than 3.0. The difference is believed to merge into the difference between the flame height on a purely flat wall and that in a wall corner[10,16,17] as W/D ratio is further increased. It is also noteworthy that flame height in a channel for W/D=3.0 and 5.0 is smaller than on a flat unconfined wall. This unexpected shortening of a flame in a wide-channel configuration is probably due to the raise of flame height at the edges of a flame by sidewalls, which is always lower than the flame height at the center only if the sidewalls are not provided.

Heat Flux to the Wall Surface

Wall surface heat fluxes measured on a flat wall, at the backwall in a channel, and at its corner have been correlated against height above the burner surface normalized by the flame height as shown in Figure 3～5. The correlation for a flat wall shown in Figure 3 is nearly consistent with the line fire correlation[10,15] except for the low Q_{mod}^* regime. The characteristic decay of heat flux between around $x/L_f=0.5$ and $x/L_f=1.0$ at the backwall in a channel, shown in Figure 4, is nearly consistent with the flat wall correlation. However, heat flux observed in $x/L_f<0.5$, solid flame, shows evident increase as the location of the measurement becomes closer to the heat source, whilst heat flux without sidewalls is nearly constant in that domain. This augmentation of surface heat flux on the backwall for low W/D ratios is attributed to the additional radiation from the sidewalls and induction of the wall flame onto the backwall due to the Coanda effect characteristic to narrow channels. Although the surface heat flux in such configuration is believed to depend partly on the temperatures of the surfaces within the channel which is further influenced by the conduction loss through each wall, it should be still noteworthy that the maximum heat flux observed for W/D=0.5, the smallest W/D ratio during this series of experiments, reached approximately $90 kW/m^2$, nearly twice to three times the typical value caused by a wall fire on a flat wall[10,15]. Dependence of heat flux on x/L_f at the corner, Figure 5, is found to be nearly consistent with that at the center of the backwall.

Increase of heat flux generally seen in narrow vertical channels should accelerate the generation of fuel gas once the channel is covered with combustible lining; this can be another cause for higher fire hazard in a vertical channel. Also, the combination of longer flame and stronger wall flame heat transfer in a narrow vertical channel suggests that preheating of the unburnt surface beyond the pyrolysis front in such configuration should be more efficient than on a flat wall of the same material. All these suggest faster flame spread in a narrow vertical channel than on a flat wall.

UPWARD FLAME SPREAD OVER COMBUSTIBLE LINING IN A VERTICAL CHANNEL

Result of the steady-flame tests suggests potential significant increase of fire hazard for $W/D \leqq 1.0$. Flame spread tests were conducted on Douglas Fir Particleboard for W/D= 0.5, 1.0 and 2.0 to verify the significance of the channel effects on wind-aided flame spread. Two-dimensional upward flame spread tests using the identical material without external radiation had already demonstrated that flame spread stop at approximately $x_{poff}= 0.025 \sim 0.036Q_\ell$. In order to make measurement of the maximum pyrolysis front height as far as possible, $Q_{mod}*$ of the heat source had to be chosen within the range of $0.35 \sim 0.5$, close to the minimum heat release rate with which a stable turbulent flame can be established above the burner.

Figure 6 shows summary of the records of observation for several W/D ratios and for the flat wall. The heat release rate is summarized as heat release rate per unit width of the whole combustible specimen, Q/(W+2D). The gradient that ○ and △ data demonstrate indicates the flame spreading velocity. Flame spread for W/D=0.5 and 1 was rather fast; pyrolysis front height became almost 6 ~ 7 times within a few seconds once the pyrolysis front height had exceeded approximately 20 cm. Stop of flame spread never occurred under these particular conditions, while both burnout and flame spread die-out took place for W/D=2. Figure 7 is a summary of the ultimate burn pattern for W/D=2 and for the flat wall. The result for W/D=2 demonstrates significant local development of fire in the corners. Figure 8 ~ 10 show summary of heat flux time history obtained at the center of the backwall and at the corner from each test. It is important to note that, for W/D=2.0, heat flux higher than $40kW/m^2$ was observed only on the gages near the ignition source, whilst such strong heat flux was observed even at higher part of the specimen for W/D=0.5 and 1.0. It is probably this strong heat flux that prevented fast burnout for W/D not larger than unity. Especially for W/D=0.5, fire lasted until the whole specimen was burnt through. Figure 11 is a summary of the heat release rate for ignition source heat output 10kW per burner-element. Heat release rate from the ignition burner, Q_b, was eliminated from this summary. The heat release time history for W/D=0.5 demonstrates dual peak typical to the sustained burning of charring materials. Heat release rate per unit effective width, Q_ℓ, can be obtained by dividing this heat release rate by the width of the whole working burner elements(0.2m for W/D=0.5 and 1, 0.4m for W/D=2, and 0.6m for W/D=3 and for the flat wall). The first peak heat release rate per unit effective width thus calculated is approximately 2,150kW/m for W/D=0.5, and 900kW/m for W/D=1. These are remarkably larger than the peak heat release for the wider channels such as 238 kW/m for W/D=2, 97kW/m for W/D=3 and 93kW/m for the flat wall.

IMPLICATION TO FIRE SAFETY

The present experiments suggest that difference in wall flame and flame spread in a vertical channel compared with those on a flat wall becomes noticeable at around W/D=2.0, and the significant augmentation of fire hazard may occur in a vertical channel with W/D ratio around 1 or less. It had taken relatively long time until the rapid flame spread started at each tests. However, this delay is partly because of the weak ignition source used for the present tests. Growth of heat release by over 10 times during approximately a minute as observed at W/D= 0.5 should be enough risky for lifesafety in the ignition room of a fire. Fire problem with combustible lining in a channel may relate not only with flame spread, since wall burning in an compartment may rise smoke layer temperature which can cause different types of fire hazard. Of course, there should be a variety of size and configuration for such vertical, or inclined, channels in the end-use conditions of building materials; grooved wooden wall of auditoria, escalators and building facade with sidewalls are only practical examples that occur to the authors. However, conclusion of previous large scale tests[3,4,5] some of which did not intend to focus this problem are still somewhat consistent with the present work; the W/D ratio of the grooves on a Oak vertical slab which caused significant upward flame spread compared with an even Oak slab was 0.6[3]. The W/D ratio for the combustible escalator trench whose fire is considered the main cause for the large number of deaths at the Kings' Cross underground fire is between 1.2 and 1.5[4]; however, existence of treads and surface grooves on the escalator are believed to increase the pyrolyzing surface and have made the flam spread faster than in a simple channel. The sidewalls which caused notable increase in heat flux to the external wall surface during a facade test[5] made a W/D=1.0 vertical channel above the window of a fire room. Recent work in construction industry suggests other design example for facade which may cause similar problem for W/D≦2.0[18]. Significance of the configuration effects to fire behavior and its relevance to fire safety should probably depend on such end-use conditions, although scale effects and other problems resulting from end-use conditions are not considered enough in the present work partly because of the limitation of the available facility and specimens. However, it is important that such effects that may arise from end-use conditions of building materials are not yet considered in most of the present fire safety regulations and there is not yet any clear prospect that reasonable fire safety evaluation can be achieved on such problem on the basis of bench-scale tests.

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TERMINOLOGY

C_p: specific heat of air, D: channel depth, H: L_f/D, L_f: flame height, Q: heat release rate, Q_b: heat release rate from the ignition burner, Q_ℓ : heat release rate per unit width, Q_{mod}^*: dimensionless heat release rate for rectangular fire source($Q/\rho C_p T_o g^{1/2} W D^{3/2}$), T_o: ambient temperature, W: channel width, g: gravitational acceleration, x: height from fire source, x_{poff}: maximum pyrolysis front height, γ: constant, ρ: density of ambient air.

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Table 1(a) Wall Flame Height Parameters(no Sidewalls), $L_f/D=\gamma \cdot Q_{mod}^{*n}$

W/D	n
0.5	0.535
1	0.566
2	0.660
3	0.613
5	0.641

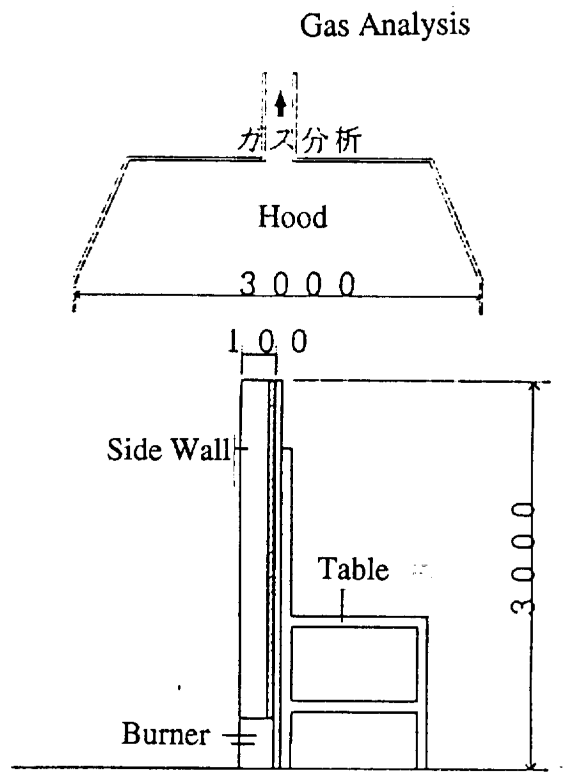
	γ				
Q* \ W/D	0.5	1	2	3	5
0.3	2.856	3.953	5.534	6.275	7.572
0.4	2.857	—	5.492	7.014	7.197
0.5	2.898	4.441	4.740	6.118	7.797
0.6	2.957	—	4.903	6.155	6.937
0.7	2.723	3.671	5.062	7.466	6.284
0.8	2.817	4.538	5.214	6.306	7.500
1.0	2.750	4.000	5.000	5.500	7.500
1.2	2.948	4.059	5.320	6.260	7.562
1.5	2.817	3.975	5.356	7.409	7.711
2.0	2.933	4.391	5.063	5.884	7.054
2.5	2.756	4.167	5.462	6.558	—
3.0	2.917	4.027	5.327	6.629	—
4.0	—	4.107	5.007	—	—
5.0	—	4.021	—	—	—
average	2.852	4.113	5.191	6.465	7.311

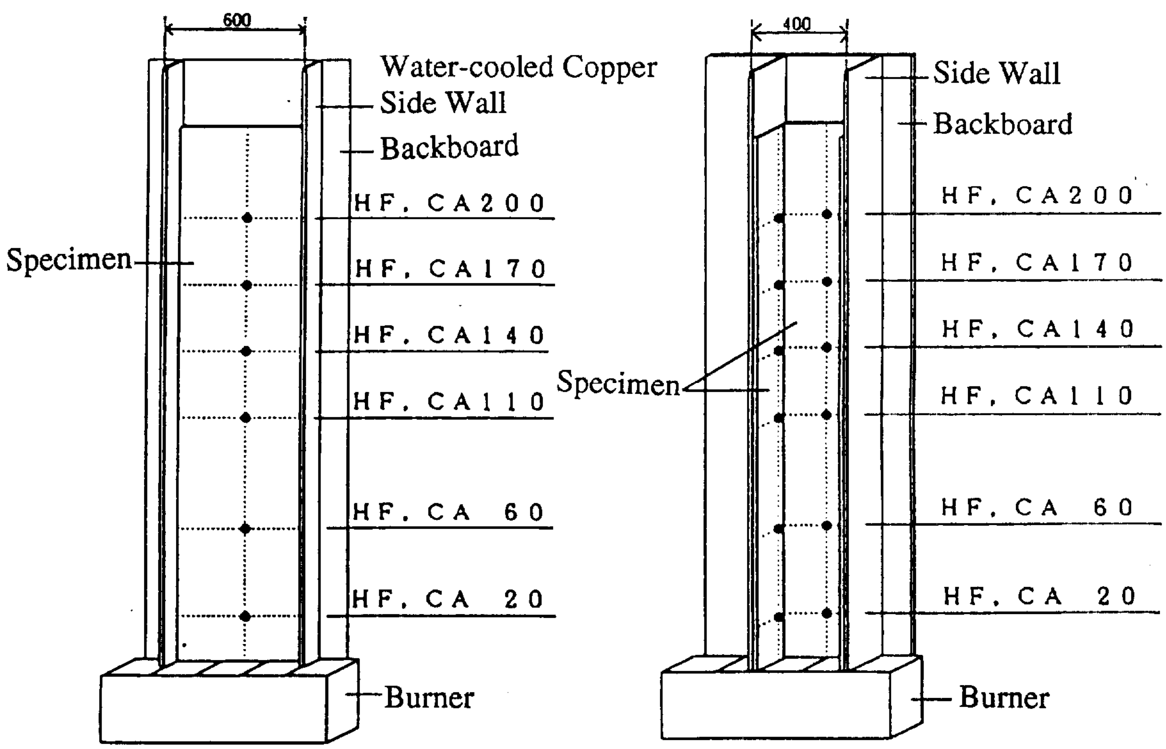
Table 1(b) Wall Flame Height Parameters(Channels), $L_f/D = \gamma \cdot Q_{mod}^{*n}$

W/D	n Backwall	n Corner
0.5	0.734	0.702
1	0.714	0.719
2	0.656	0.639
3	0.513	0.649
5	0.706	0.667

γ Backwall					
Q* \ W/D	0.5	1	2	3	5
0.3	4.074	4.725	5.507	5.564	5.849
0.4	4.757	——	5.472	5.600	6.684
0.5	4.474	4.921	5.515	6.422	6.525
0.6	5.010	——	5.592	5.848	6.454
0.7	4.817	4.515	5.504	5.404	6.432
0.8	4.678	5.277	5.209	5.606	6.438
1.0	4.500	5.500	5.000	5.000	6.000
1.2	4.179	5.267	5.767	5.009	6.594
1.5	4.702	4.866	5.365	4.873	6.384
2.0	4.764	4.572	5.077	5.606	6.346
2.5	4.599	4.938	5.482	5.937	——
3.0	4.278	5.248	5.351	6.261	——
4.0	——	4.831	5.639	——	——
5.0	——	4.754	——	——	——
average	4.486	4.951	5.422	5.594	6.371

γ Corner					
Q* \ W/D	0.5	1	2	3	5
0.3	4.234	4.753	6.475	6.553	7.813
0.4	4.408	——	6.286	7.250	6.449
0.5	4.158	4.115	6.229	7.056	6.351
0.6	4.728	——	5.544	6.269	6.327
0.7	4.872	5.169	6.280	6.302	6.977
0.8	4.712	5.870	6.343	6.357	6.383
1.0	4.500	6.000	6.000	6.000	6.000
1.2	4.155	5.263	6.230	5.775	7.084
1.5	4.641	5.230	6.560	6.149	6.867
2.0	4.660	4.860	6.422	6.377	7.243
2.5	4.466	4.916	6.403	6.345	——
3.0	4.130	5.220	6.195	6.372	——
4.0	——	4.798	5.979	——	——
5.0	——	4.716	——	——	——
average	4.472	5.076	6.227	6.400	6.749





(a) Flat Wall Flame Spread Test

(b) Vertical Channel

Figure 1 Vertical Channel Specimen and Experimental Set Up

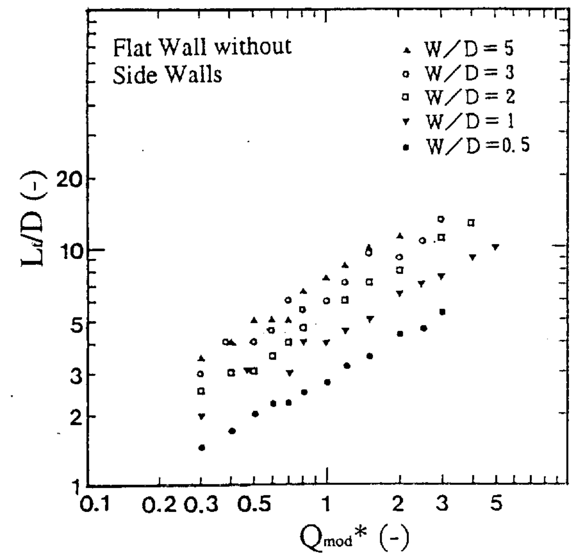


Figure 2(a) Flat Wall

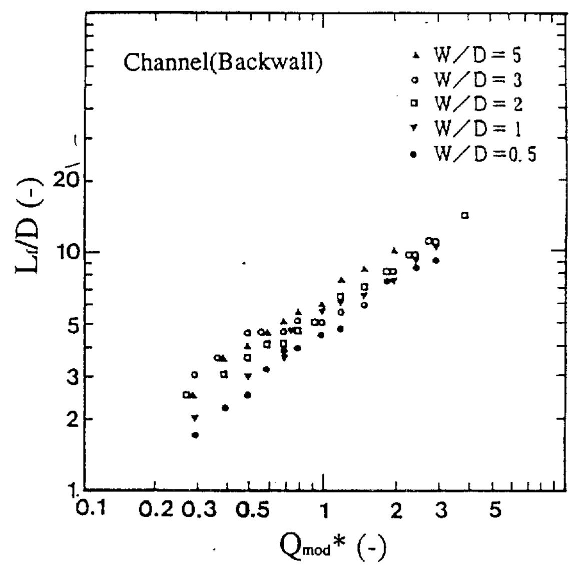


Figure 2(b) Flame Height Measured at the Center of the Backwall of a Channel

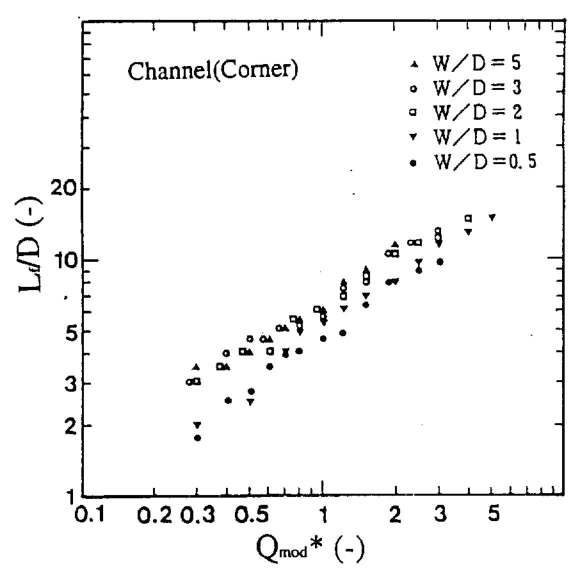


Figure 2(c) Flame Height Measured at the Corner between the Backwall and a Sidewall of a Channel

Figure 2 Flame Height vs Dimensionless Heat Release Rate, $Q_{mod}*$

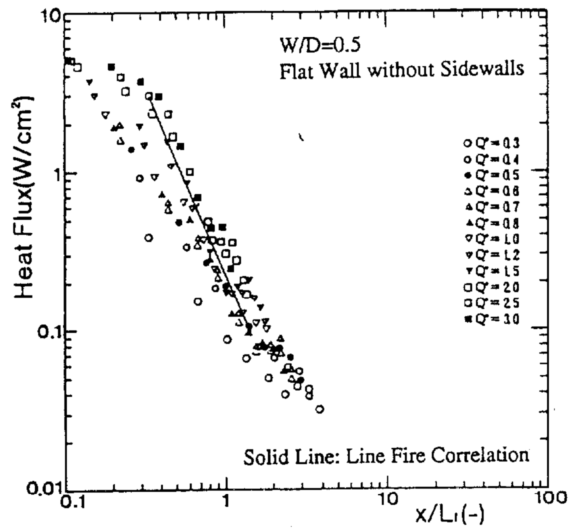


Figure 3(a) W/D=0.5

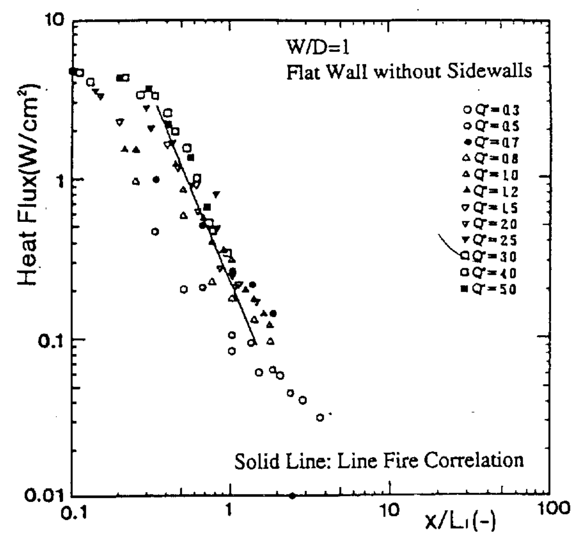


Figure 3(b) W/D=1.0

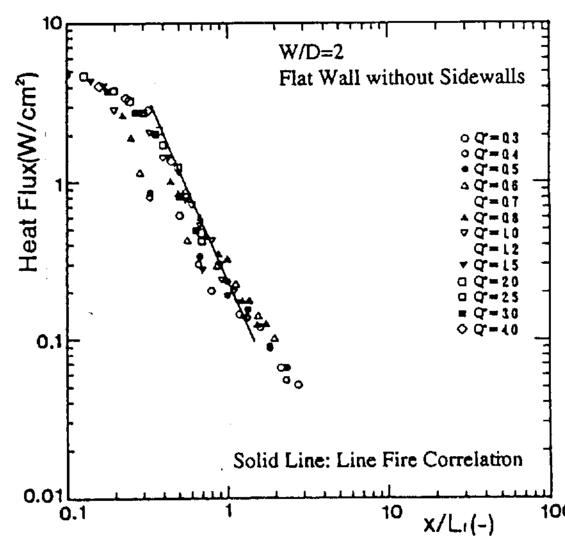


Figure 3(c) W/D=2.0

Figure 3 Heat Flux to Wall Surface vs Height Normalized by Flame Height, Flat Wall

Figure 3 Heat Flux to Wall Surface vs Height Normalized by Flame Height, Flat Wall(cont.)

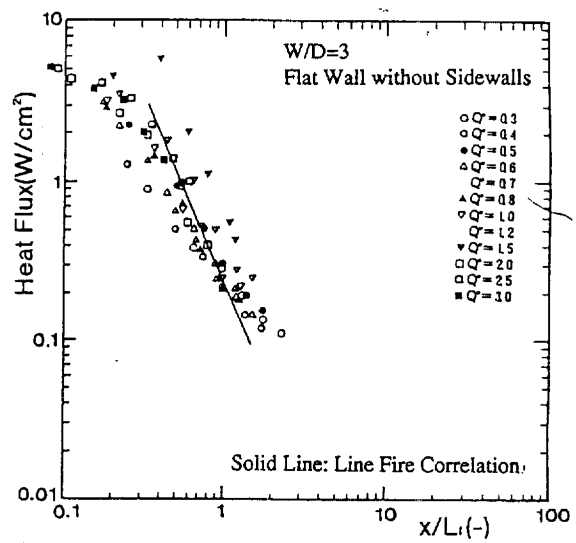


Figure 3(d) W/D=3.0

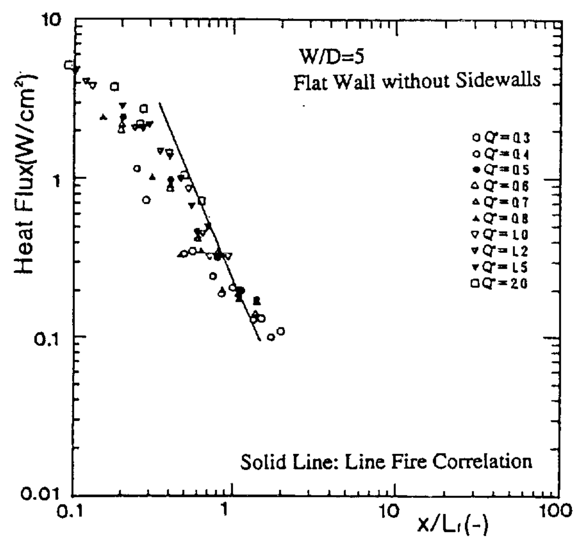


Figure 3(e) W/D=5.0

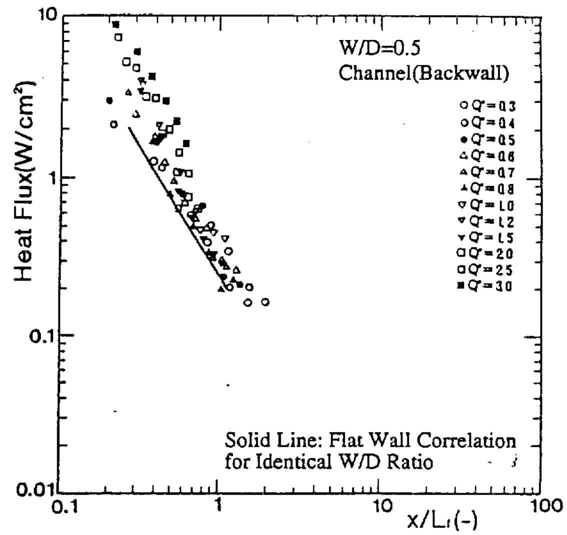


Figure 4(a) W/D=0.5

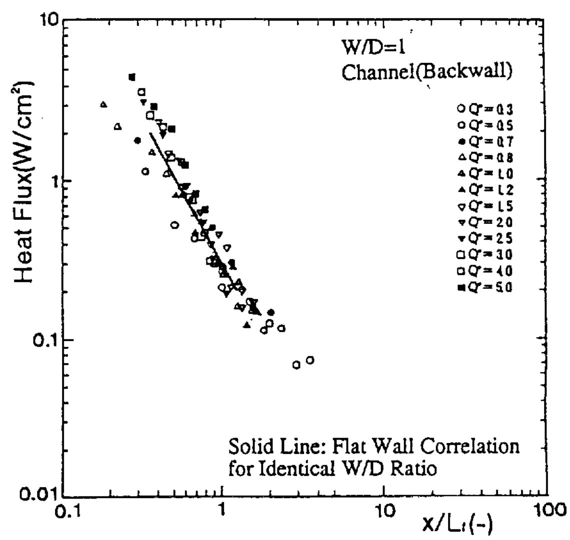


Figure 4(b) W/D=1.0

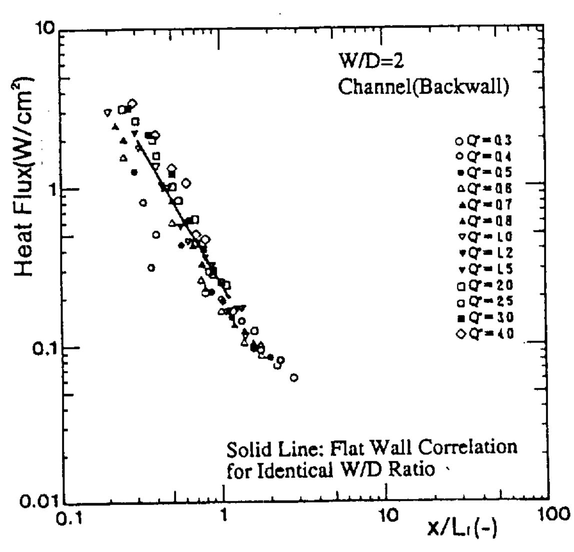


Figure 4(c) W/D=2.0

Figure 4 Wall Heat Flux vs Normalized Height in Channel, Center of the Backwall

Figure 4 Wall Heat Flux vs Normalized Height in Channel, Center of the Backwall(Cont.)

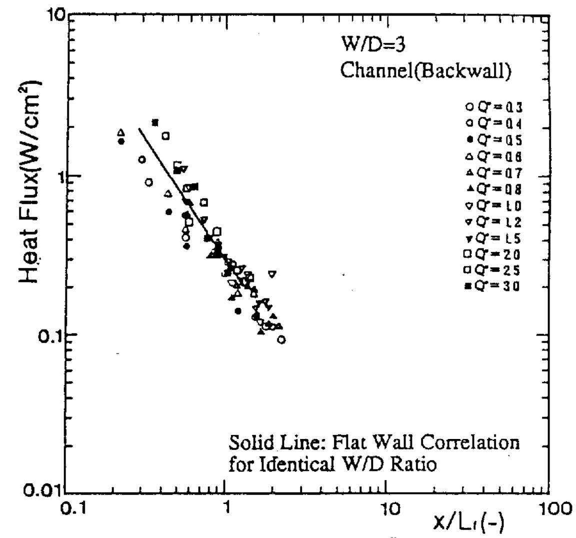


Figure 4(d) W/D=3.0

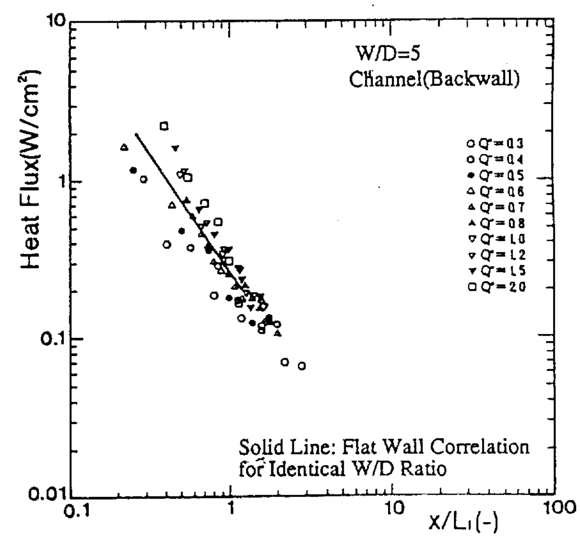


Figure 4(e) W/D=5.0

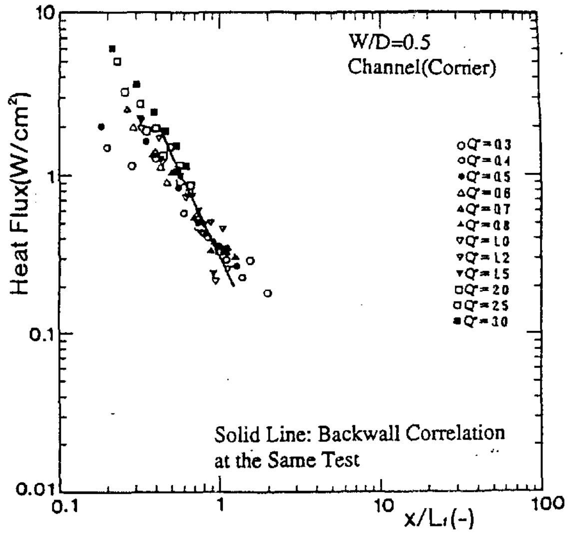


Figure 5(a) W/D=0.5

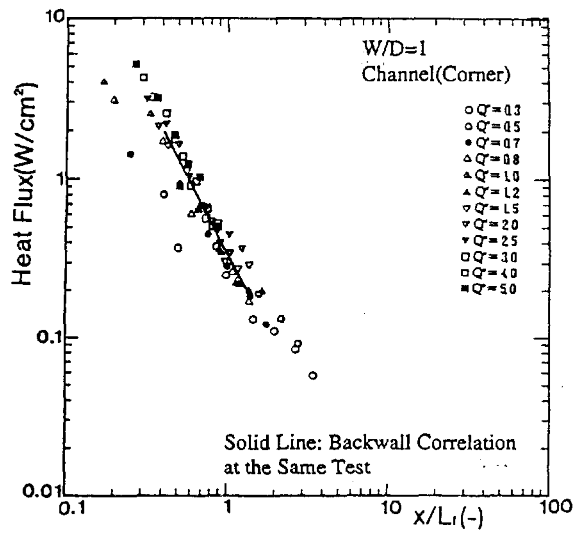


Figure 5(b) W/D=1.0

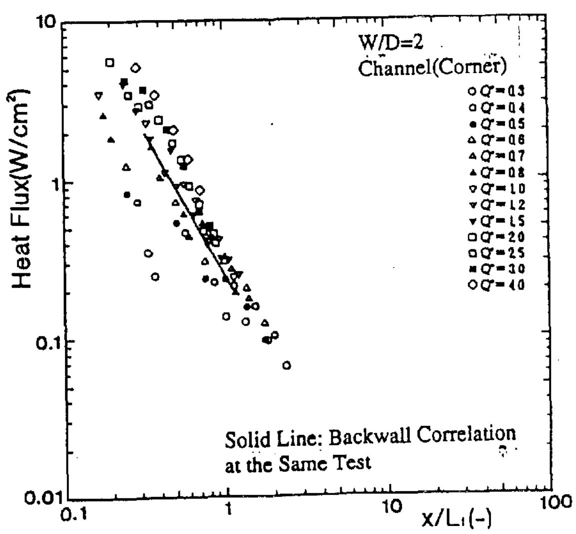


Figure 5(c) W/D=2.0

Figure 5 Wall Heat Flux vs Normalized Height in Channel, Backwall/Sidewall Corner

Figure 5 Wall Heat Flux vs Normalized Height in Channel, Backwall/Sidewall Corner(cont.)

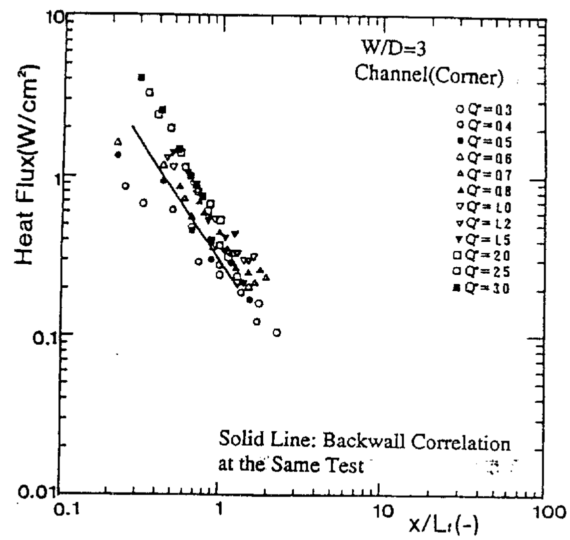


Figure 5(d) W/D=3.0

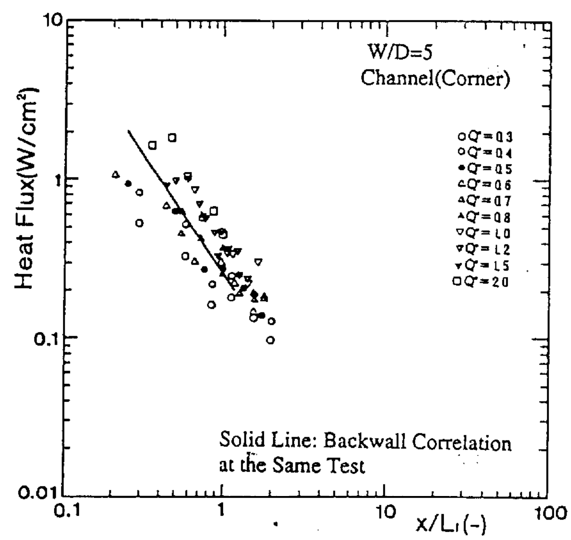


Figure 5(e) W/D=5.0

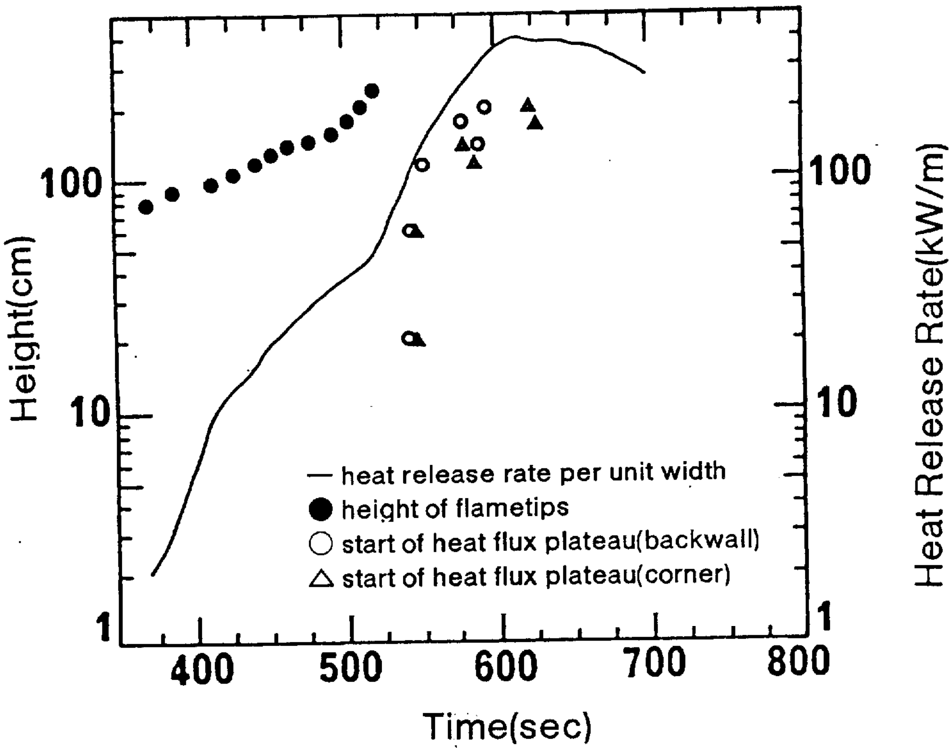


Figure 6(a) W/D=0.5, Q_b=20kW

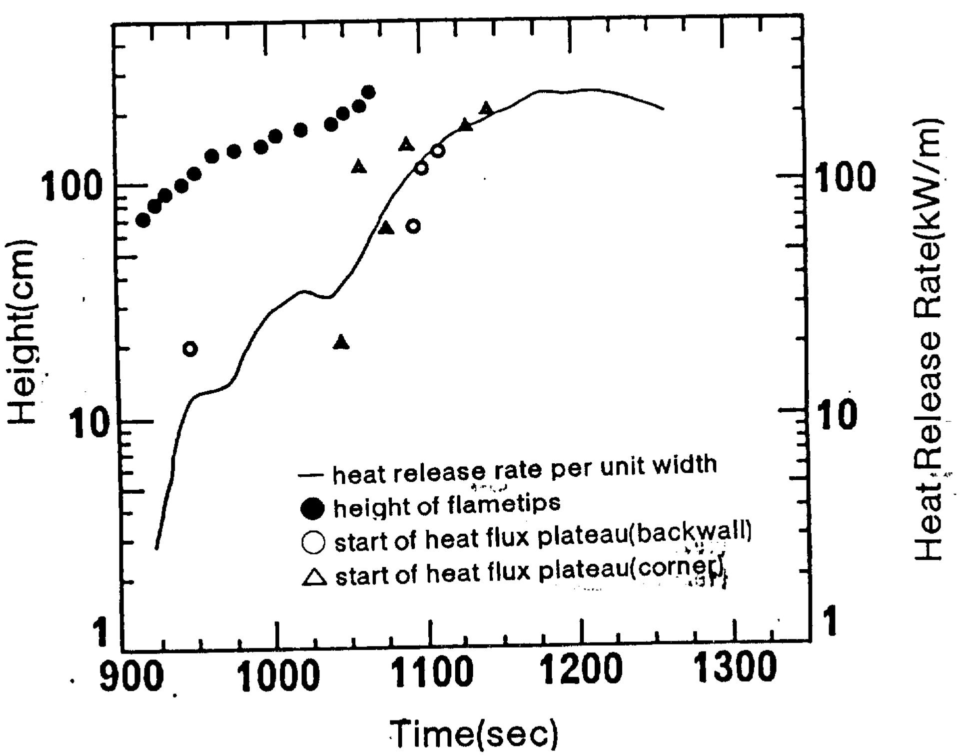
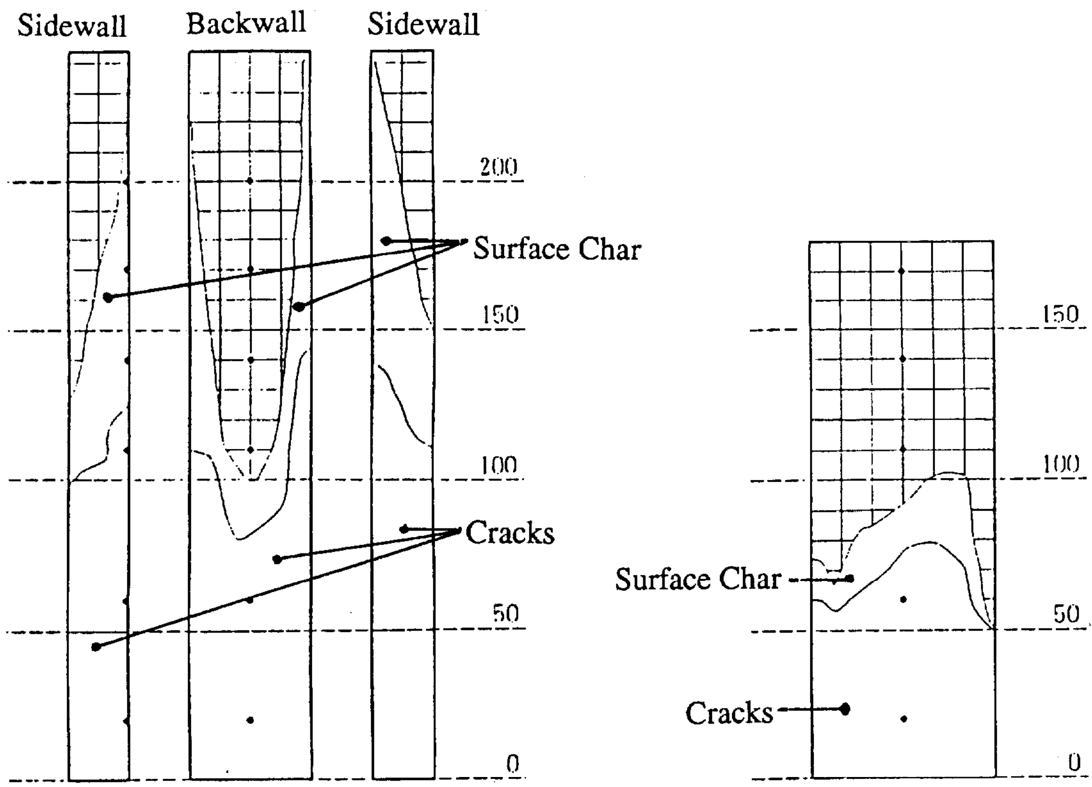


Figure 6(b) W/D=1, Q_b=10KW
Figure 6 Summary Observation Records during Flame Spread Test



(a) W/D=2

(b) Flat Wall

Figure 7 Ultimate Burn Patterns(Particleboard), Q_b=10kW/burner element

Figure 6 Summary Observation Records during Flame Spread Test(Cont.)

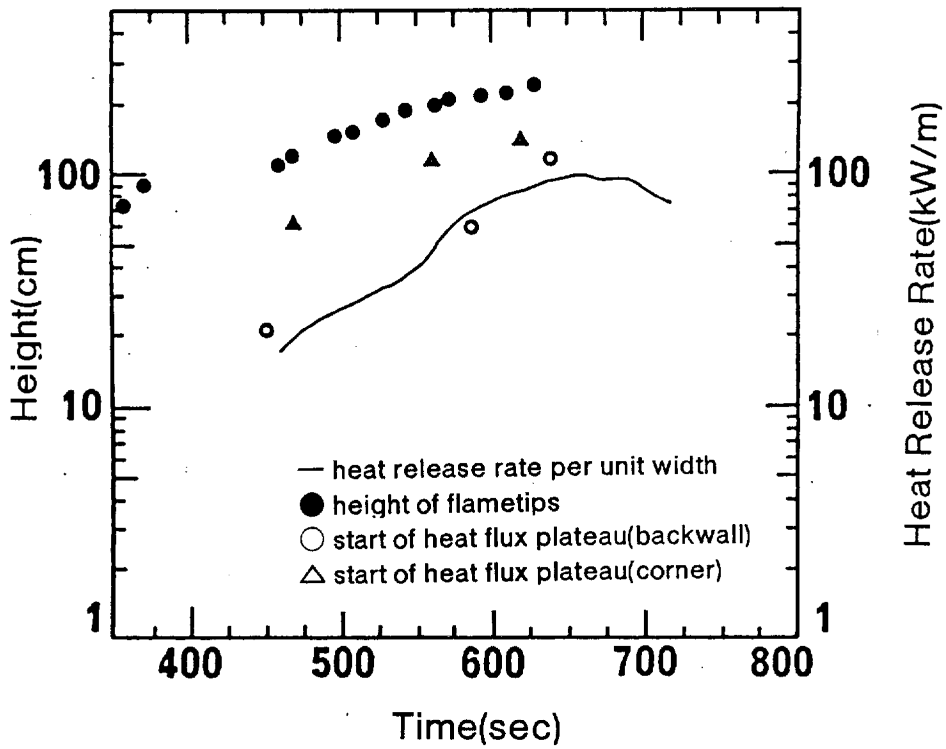


Figure 6(c) W/D=2, Q_b=20kW

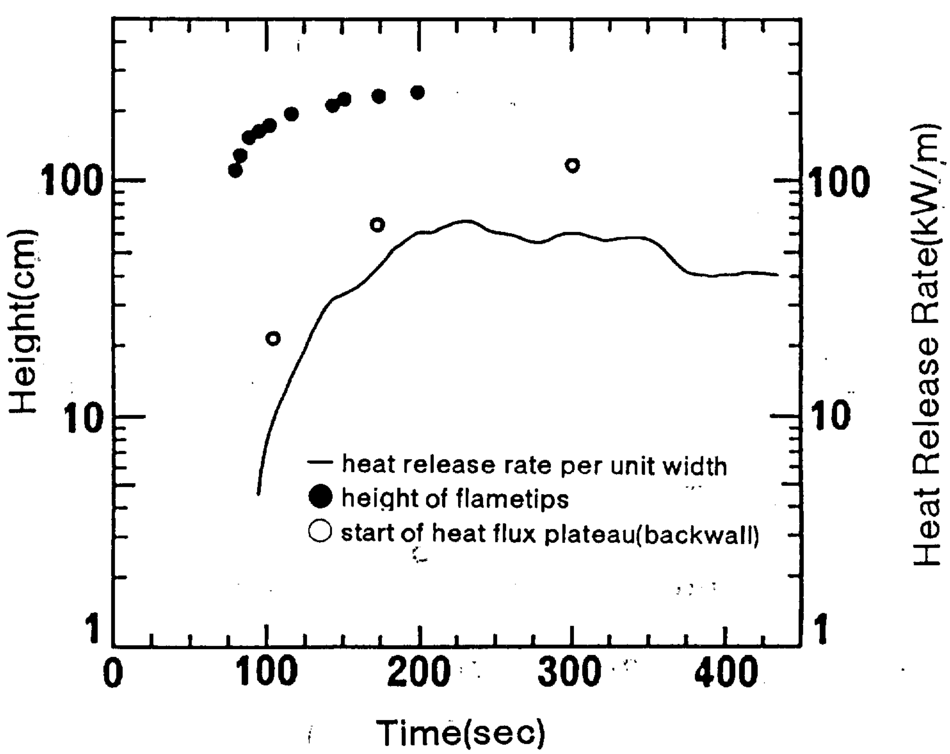


Figure 6(d) Flat Wall, Q_b=60kW

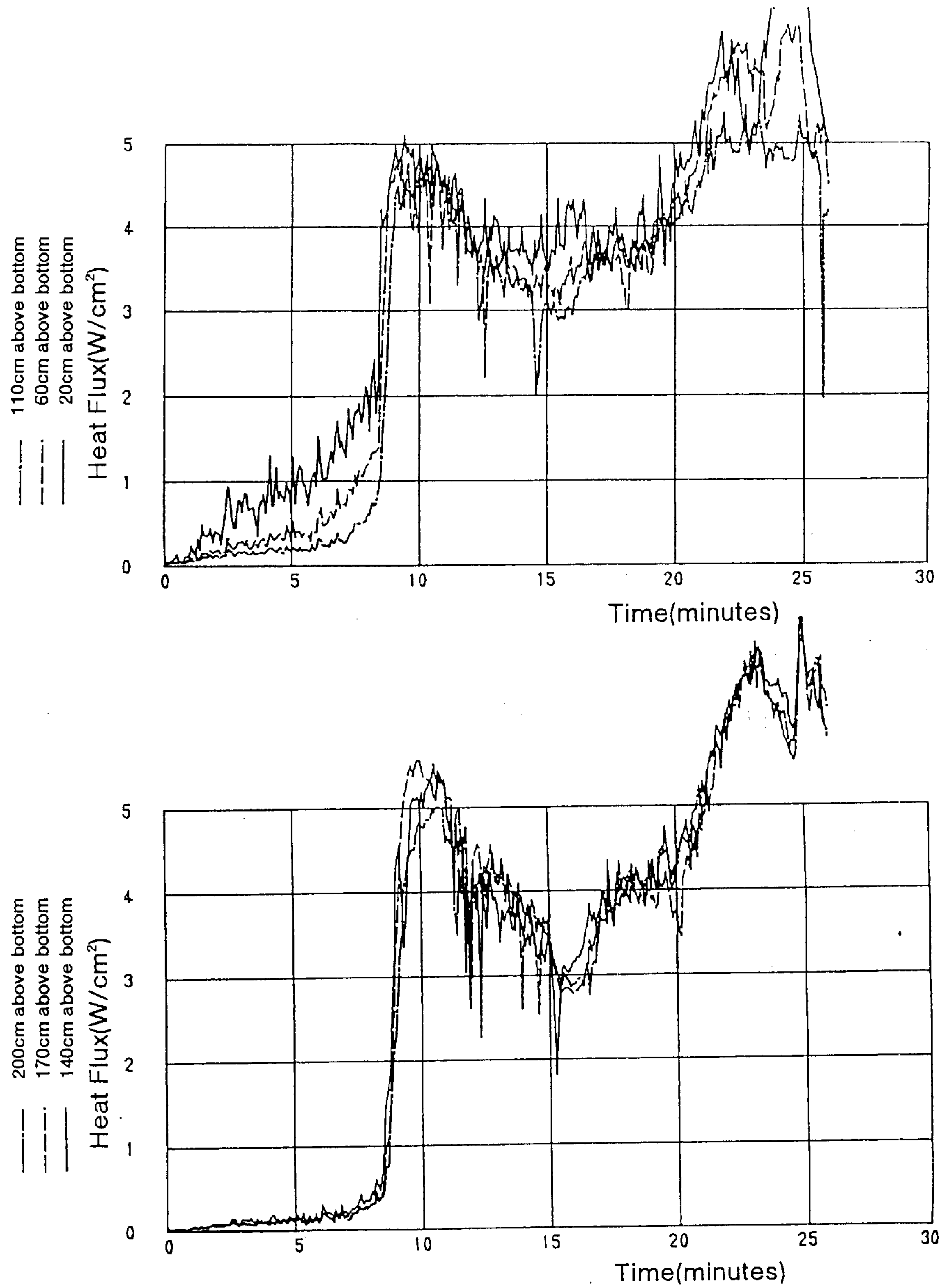
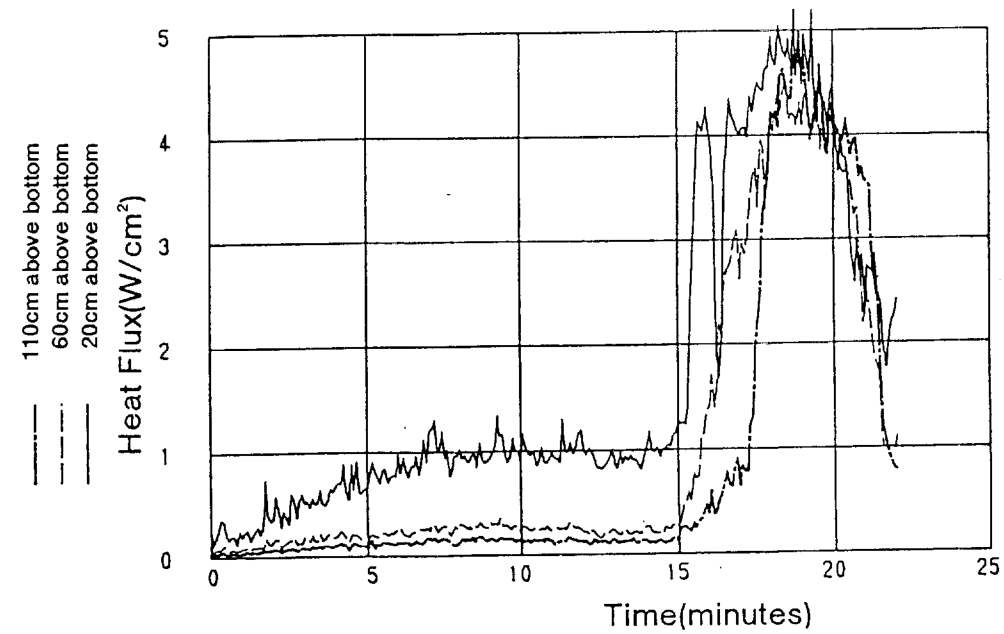


Figure 8 Time History of Heat Flux in Channel, W/D=0.5, Q_b=20kW, Center of Backwall



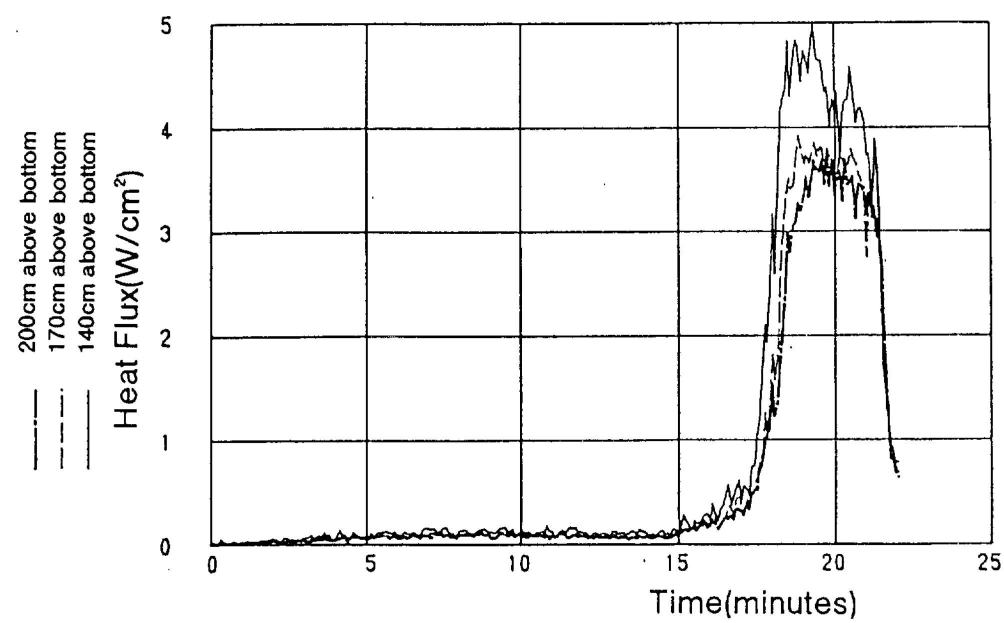
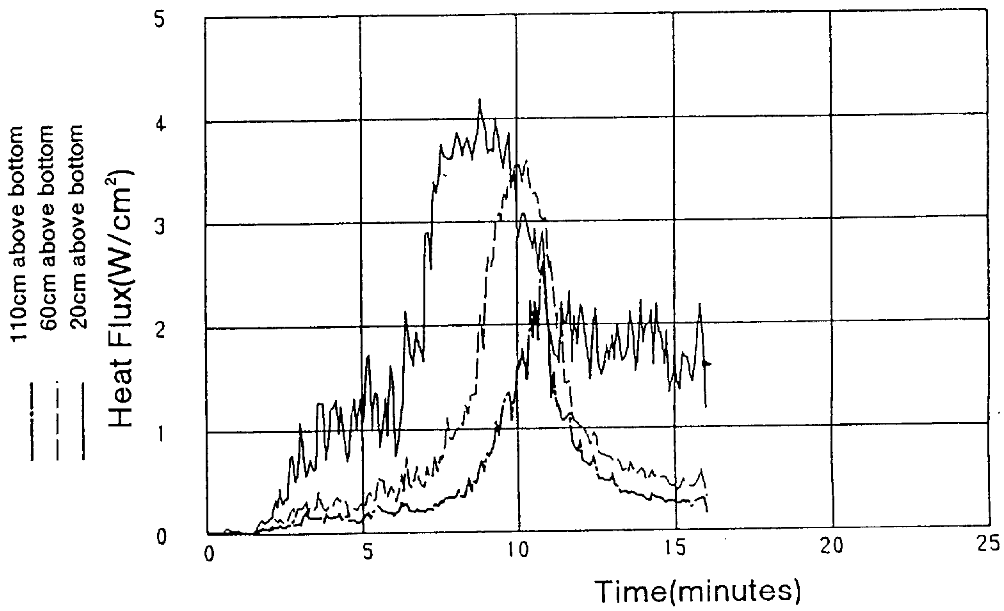


Figure 9 Time History of Heat Flux in Channel, W/D=1.0, , Q_b=10kW, Center of Backwall



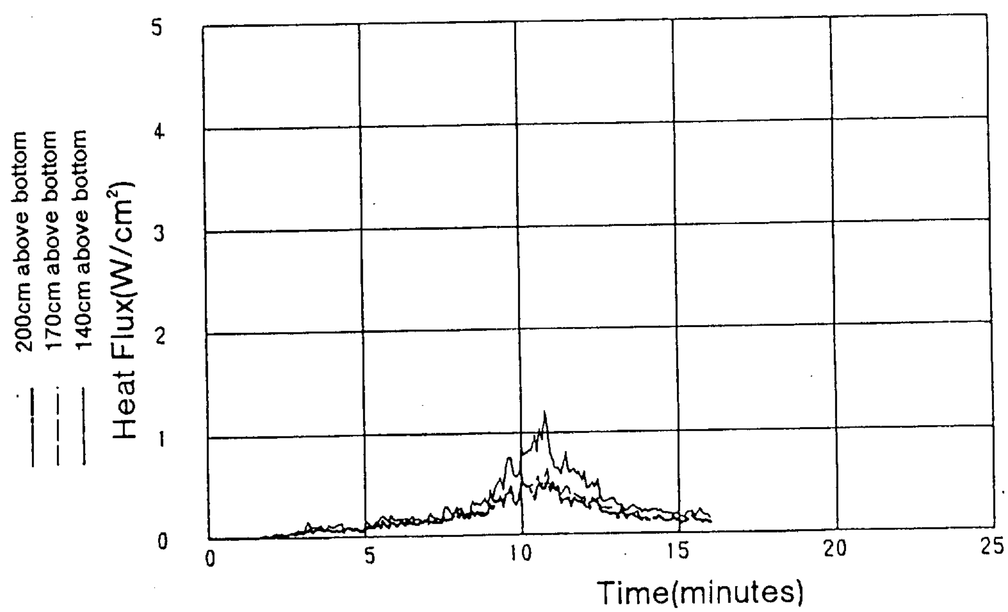


Figure 10 Time History of Heat Flux in Channel, W/D=2.0, Q_b=20kW, Center of Backwall

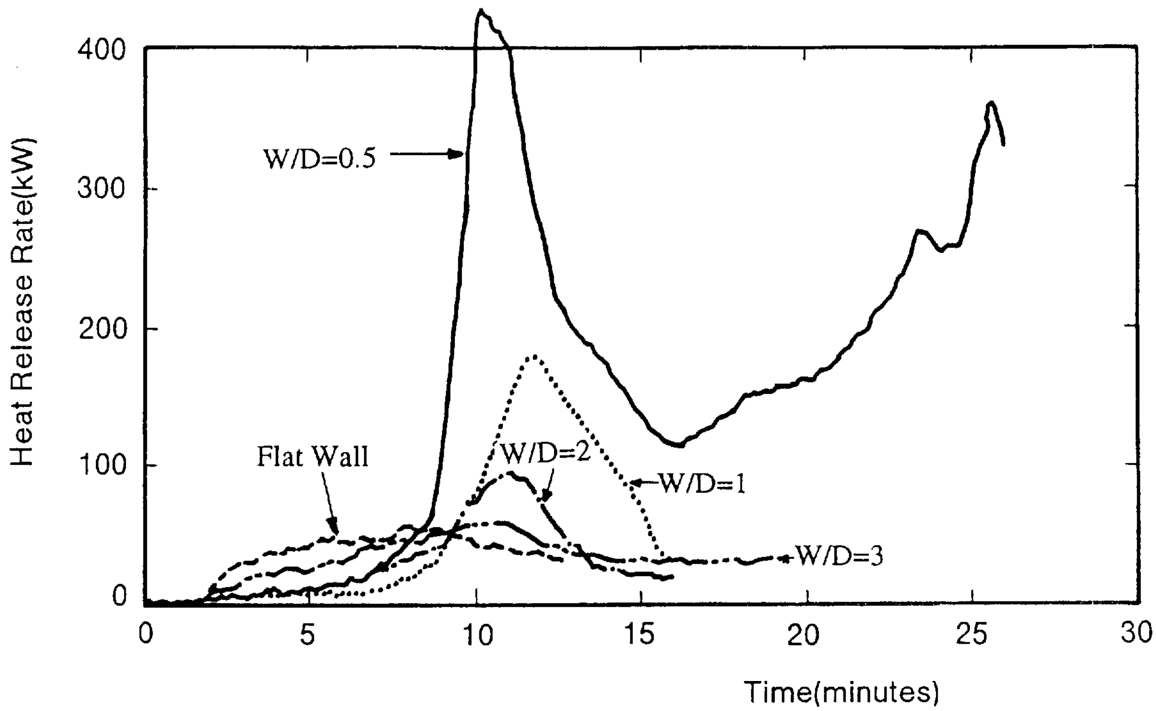


Figure 11 Time History of Heat Release Rate at Flame Spread Tests(Qb= 10kW/burner element)

Discussion

James Quintiere: May I ask two quick questions? First, would you agree that the different models are really based on the same physics, but they just have some different approximations?

Yuji Hasemi: Yes.

James Quintiere: My experience in some work we are doing now suggests that there are some other aspects to this problem. One is the effect of the ignition source which influences the flame height and the heat flux. And the second is transient burning. Particularly, the influence of thin materials and burnout. Just as an anecdote, there were some serious fires in New York City in stairways in which there were something like sixteen coats of paint. Had the paint coats been fewer, there would probably have been no fire spread. Do you agree that these are two significant effects? What is your experience?

Yuji Hasemi: We are currently studying that.

Ronald Alpert: I just want to call you attention to reference 3 in your concurrent flame spread paper. In that reference, Orloff and Markstein, in the Fifteenth International Symposium on Combustion, conducted a study with a gas burner in which they rotated the burner for different angles and discovered that effect back in 1974.

Yuji Hasemi: Yes, indeed I am aware of the experiment. However, they are not utilized in the practice of fire separation. We hope that as researchers, we should promote taking the results into practice so they would be used in actual situations.